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# Measurement of charged-particle event shape variables in $\sqrt{s} = 7$ TeV proton-proton interactions with the ATLAS detector

The ATLAS Collaboration

## Abstract

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## I. INTRODUCTION

Event shape variables describe the properties of the energy flow and the structure of hadronic events. In this analysis, three event shape observables [1, 2] are measured: the transverse thrust, the thrust minor and the transverse sphericity, each built from the charged particle momenta using tracking information from proton-proton collisions at  $\sqrt{s} = 7$  TeV collected with the ATLAS detector [3]. Event shape observables are among the simplest experimentally measured quantities and depending on the events being considered, may have sensitivity to both perturbative and non-perturbative aspects of Quantum Chromodynamics (QCD).

Event shapes have been investigated extensively in  $e^+e^-$  and  $ep$  deep-inelastic scattering experiments to study the energy flow in the hadronic final state, test the predictions of perturbative QCD and to extract a precise value for the strong coupling constant  $\alpha_s$  [4–11]. In  $p\bar{p}$  collisions at the Tevatron, the dependence of the event shape observables on the transverse energy of the leading jet and on contributions from the underlying event has been studied [12]. At the Large Hadron Collider (LHC), event shape observables have recently been studied in inclusive interactions [13] and multijet events [14, 15].

The study of event shape observables in inclusive minimum-bias events plays an important role in understanding the nature of soft-QCD processes at the LHC center-of-mass energies [16], where “soft” refers to interactions with low momentum transfer between the scattering particles. Soft interactions cannot be reliably calculated from theory and are thus generally described by phenomenological models, usually implemented in Monte Carlo (MC) event generators. These models contain many parameters whose values are *a priori* unknown and thus need to be constrained by measurements. Inclusive and semi-inclusive observables sensitive to soft-QCD processes have been measured at the LHC by ATLAS [17–19], CMS [20, 21] and ALICE [22, 23]. The measurements presented in this paper will further constrain the event generator models, which encapsulate our understanding of these soft processes.

In this analysis, the event shape observables are constructed from six or more primary charged particles in the pseudorapidity range  $|\eta| < 2.5$  and with transverse momentum  $p_T > 0.5$  GeV [24]. Primary charged particles are defined as those with a mean proper lifetime  $\tau > 30$  ps, produced either directly in the  $pp$  interaction or from the subsequent decay of particles with a shorter lifetime. The particle level refers to particles as they emerge from the proton-proton interaction. The detector level corresponds to tracks as measured by the detector(s) after interaction with the material, and including the detector response. The results are corrected for detector effects, using simulation, to obtain distributions of the event shape variables defined at particle level which can be directly compared to MC models.

This paper is organized as follows: Section II defines the event shape variables; the detector is described in Section III; Section IV discusses the MC models used in this analysis; Section V and Section VI respectively describe the event selections and background contributions. The correction of the data back to particle level, and estimation of the systematic uncertainties are described in Section VII and Section VIII; the results are discussed in Section IX and finally the conclusions are presented in Section X.

## II. EVENT SHAPE OBSERVABLES

In particle collisions, event shape observables describe the geometric properties of the energy flow in the final state. A single event shape variable can distinguish in a continuous way between configurations in which all the particles are flowing (forward and backward) along a single axis and configurations where the energy is distributed more uniformly over the  $4\pi$  solid angle. If defined as the ratio of measured quantities, the corresponding systematic uncertainties may be small.

In hadron collisions, where the center-of-mass frame of the hard interaction is usually boosted along the beam axis, event shape observables are often defined in terms of the transverse momenta, which are Lorentz-invariant

under such boosts. Different formulations of event shape observables are possible; the most intuitive is to calculate the event shape from all particles in an event. These are denoted as *directly global* event shapes [1, 2]. In most hadronic collisions, it is not usually possible to detect all particles in an event due to the finite detector acceptance limited at small angles by the presence of the beam pipe. Event shapes which include only particles from a restricted phase space in pseudorapidity  $\eta$ , are called *central event shapes*: in this analysis charged particles within  $|\eta| < 2.5$  are used. These central event shape values are nevertheless sensitive to non-perturbative effects at low momentum transfer and can be experimentally useful observables.

The thrust is one of the most widely used event shape variables. At hadron colliders the transverse thrust for a given event is defined as:

$$T_{\perp} = \max_{\hat{n}} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}|}{\sum_i |\vec{p}_{T,i}|} \quad (1)$$

where the sum is performed over the transverse momenta  $\vec{p}_{T,i}$  of all particles in the event. The thrust axis  $\hat{n}_T$  is the unit vector  $\hat{n}$  that maximizes the ratio in Eq. 1. The transverse thrust ranges from  $T_{\perp} = 1$  for a perfectly balanced, pencil-like, dijet topology to  $T_{\perp} = \langle |\cos \psi| \rangle = 2/\pi$  for a circularly symmetric distribution of particles in the transverse plane, where  $\psi$  is the azimuthal angle between the thrust axis and each respective particle. Since many event shape variables vanish in a balanced dijet topology, it is convenient to define  $\tau_{\perp} = 1 - T_{\perp}$ , which shares this property. Hereafter, any discussion of the observable called transverse thrust will refer to the quantity  $\tau_{\perp}$ .

The thrust axis  $\hat{n}_T$  and the beam axis  $\hat{z}$  define the *event plane*. The transverse thrust minor measures the out-of-event-plane energy flow:

$$T_M = \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_m|}{\sum_i |\vec{p}_{T,i}|}, \quad \hat{n}_m = \hat{n}_T \times \hat{z}. \quad (2)$$

The transverse thrust minor is 0 for a pencil-like event in  $\phi$  and  $2/\pi$  for an isotropic event.

Another widely used event shape variable is the sphericity,  $S$ , which describes the event energy flow based on the momentum tensor,

$$S^{\alpha\beta} = \frac{\sum_i p_i^{\alpha} p_i^{\beta}}{\sum_i |\vec{p}_i|^2}, \quad (3)$$

where the Greek indices represent the  $x$ ,  $y$ , and  $z$  components of the momentum of the particle  $i$ . The sphericity of the event is defined in terms of the two smallest eigen-

values of this tensor,  $\lambda_2$  and  $\lambda_3$ :

$$S = \frac{3}{2}(\lambda_2 + \lambda_3). \quad (4)$$

The sphericity has values between 0 and 1, where a balanced dijet event corresponds to  $S = 0$  and an isotropic event to  $S = 1$ . Sphericity is essentially a measure of the summed  $p_T^2$  with respect to the event axis [25, 26], where the event axis is defined as the line passing through the interaction point and oriented along the eigenvector associated with the largest eigenvalue  $\lambda_1$ . Similar to transverse thrust, the transverse sphericity,  $S_{\perp}$ , is defined in terms of the transverse components only:

$$S^{xy} = \sum_i \frac{1}{|\vec{p}_{T,i}|^2} \begin{bmatrix} p_{x,i}^2 & p_{x,i} p_{y,i} \\ p_{x,i} p_{y,i} & p_{y,i}^2 \end{bmatrix} \quad (5)$$

and

$$S_{\perp} = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}}, \quad (6)$$

where  $\lambda_2^{xy} < \lambda_1^{xy}$  are the two eigenvalues of  $S_{xy}$ .

The following distributions are measured:

- Normalized distributions:  $\frac{1}{N_{ev}} \frac{dN_{ev}}{d\tau_{\perp}^{ch}}$ ,  $\frac{1}{N_{ev}} \frac{dN_{ev}}{dT_M^{ch}}$ ,  $\frac{1}{N_{ev}} \frac{dN_{ev}}{dS_{\perp}^{ch}}$ ;
- Average values:  $\langle \tau_{\perp}^{ch} \rangle$ ,  $\langle T_M^{ch} \rangle$  and  $\langle S_{\perp}^{ch} \rangle$  as functions of  $N_{ch}$  and  $\sum p_T$ ;

where  $N_{ev}$  is the number of events with six or more charged particles within the selected kinematic range;  $N_{ch}$  is the number of charged particles in an event;  $\sum p_T$  is the scalar sum of the transverse momenta of the charged particles in the event. The event shape observables  $\tau_{\perp}^{ch}$ ,  $T_M^{ch}$  and  $S_{\perp}^{ch}$  are defined as above, with the superscript indicating that they are constructed from charged particles. The three normalized differential distributions are studied separately for  $p_T^{lead}$  above 0.5 GeV, 2.5 GeV and 5 GeV, where  $p_T^{lead}$  is the transverse momentum of the highest  $p_T$  (leading) charged particle.

### III. THE ATLAS DETECTOR

The ATLAS detector [3] covers almost the full solid angle around the collision point with layers of tracking detectors, calorimeters and muon chambers. The components that are relevant for this analysis are the tracking detectors. The inner tracking detector has full coverage in azimuthal angle  $\phi$  and covers the pseudorapidity range  $|\eta| < 2.5$ . It consists of a silicon pixel detector (pixel), a semiconductor tracker (SCT) and a straw-tube transition radiation tracker (TRT). These detectors are located at a radial distance from the beam line of 50.5–150 mm, 299–560 mm and 563–1066 mm, respectively, and are immersed in a 2 T axial magnetic field. The inner detector barrel (end-caps) consist of 3 ( $2 \times 3$ ) pixel layers, 4

( $2 \times 9$ ) layers of double-sided silicon strip modules, and 73 ( $2 \times 160$ ) layers of TRT straw-tubes. These detectors have position resolutions typically of 10  $\mu\text{m}$ , 17  $\mu\text{m}$  and 130  $\mu\text{m}$  for the  $r$ - $\phi$  coordinate. The pixel and SCT detectors provide measurements of the  $r$ - $z$  coordinate with typical resolutions of 115  $\mu\text{m}$  and 580  $\mu\text{m}$ , respectively. The TRT acceptance is  $|\eta| < 2.0$ . A track traversing the barrel typically has 11 silicon hits (3 pixel clusters and 8 strip clusters) and more than 30 straw-tube hits.

The measurements presented here rely on the minimum-bias trigger scintillator (MBTS) system. The MBTS detectors are mounted at each end of the tracking detector at  $z = \pm 3.56$  m and are segmented into eight sectors in azimuth and two concentric rings in pseudorapidity ( $2.09 < |\eta| < 2.82$  and  $2.82 < |\eta| < 3.84$ ). The MBTS trigger was configured to require at least one hit above threshold from either side of the detector in coincidence with a fast beam pickup device ensuring that the event is compatible with a bunch crossing.

#### IV. MONTE CARLO MODELS

Monte Carlo event samples are used to compute detector acceptance and reconstruction efficiency, determine background contributions, correct the measurements for detector effects, and to calculate systematic uncertainties. Finally, different phenomenological models implemented in the MC generators are compared to the data corrected to the particle level.

The PYTHIA6 [27], PYTHIA8 [28] and Herwig++ [29, 30] event generators were used to produce the simulated event samples for the analysis. These generators implement leading-logarithmic parton shower models matched to leading-order matrix element calculations with different hadronization models and ordering for the parton shower. The PYTHIA6 and PYTHIA8 generators use a hadronization model based upon fragmentation of color strings and a  $p_T$ -ordered or virtuality ordered shower, whereas the Herwig++ generator implements a cluster hadronization scheme with parton showering ordered by emission angle. Different settings of model parameters optimized, or tuned to reproduce the existing experimental data have been used for the MC generators.

The following Monte Carlo generators were used: PYTHIA6 with tunes AMBT1 [31], AMBT2B [32], DW [33], Z1 [34]; PYTHIA8 tune A2 [35]; and Herwig++ tune UE7-2 [36]. For PYTHIA 6, version 6.425 was used in all cases except for tune DW, for which version 6.421 was used.

The AMBT1 (ATLAS Minimum Bias Tune 1) is the first LHC data tune of PYTHIA 6 from ATLAS, and uses the diffraction suppressed part of the early minimum-bias measurements [17]. This employs the MRST LO\*\* [37] parton distribution functions (PDFs) and the PYTHIA 6  $p_T$ -ordered parton shower. The PYTHIA 6 DW tune uses a virtuality ordered parton shower and a multi-parton interaction (MPI) model not interleaved with the initial state radiation (ISR). This tune was constructed to de-

scribe CDF Run II underlying event data, and uses the CTEQ5L1 PDF set. The AMBT2B tune is an improved version of AMBT1 tune, which optimizes parameters controlling the ISR cutoff and evolution by including ATLAS track-jet [38], jet shape [39] and dijet decorrelation [40] data. The tune with CTEQ6L1 PDF is used here, and provides one of the best available descriptions of existing minimum-bias data at  $\sqrt{s} = 7$  TeV. The Z1 tune developed by the CMS collaboration with the CTEQ5L PDF set is based on AMBT1, but uses CMS charged-particle jet underlying event data to obtain a better description of the underlying event. The PYTHIA 8 generator uses the MPI model interleaved with both ISR and final state radiation (FSR). The ATLAS minimum-bias tune of PYTHIA8, A2 with the MSTW2008LO PDF, which provides a good description of minimum-bias data at  $\sqrt{s} = 7$  TeV, is used. For Herwig++, version 2.5.1 is used with a 7 TeV underlying event tune, UE7-2, which employs color reconnection, and uses the MRST LO\*\* PDF.

The reference tune for this analysis is chosen to be PYTHIA 6 AMBT1. Samples generated with this tune were passed through the ATLAS detector and trigger simulations [41] and then reconstructed and analyzed using the same procedure and software that are used for the data. Reconstructed MC events are then used to correct the data for detector effects. A sample generated with an older version of Herwig++, 2.5.0 with no additional tuning, was also passed through the full detector simulation and the analysis chain for systematic studies of unfolding corrections.

#### V. EVENT AND TRACK SELECTION

The collision data used for the analysis presented here were collected in April 2010 with a minimal prescale factor for the minimum-bias trigger. The only further requirement for selecting the data sample is that the MBTS trigger and all inner detector subsystems were at nominal operating conditions. In each event the reconstructed vertices are ordered by the  $\sum p_T^2$  over the tracks assigned to each vertex, and the vertex with the highest  $\sum p_T^2$  is taken as the primary interaction vertex of the event. To reduce the contribution from beam-related backgrounds and decays of long-lived particles, and to minimize the systematic uncertainties, events are rejected if they contain any other vertex reconstructed with four or more tracks.

If there is only one vertex in the event, or if any additional vertex in the event has three or fewer tracks, all tracks from the event that pass the track selection described next are retained. After this selection, the fraction of events with more than one proton-proton interaction in the same bunch crossing (referred to as pile-up) is found to be approximately 0.1% and this residual contribution is therefore neglected. The average number of  $pp$  interactions per bunch crossing during this data taking period was less than 0.15, indicating a negligible pile-

up contribution. The MC samples used have no pile-up contribution.

Events are required to contain at least six tracks that fulfill the following criteria:

- $p_T > 0.5$  GeV;
- a minimum of one pixel and six SCT hits;
- a hit in the innermost pixel layer, if the corresponding pixel module was active;
- transverse and longitudinal impact parameters with respect to the primary vertex,  $|d_0| < 1.5$  mm and  $|z_0| \sin \theta < 1.5$  mm;
- a track-fit probability  $\chi^2 > 0.01$  in order to remove mis-measured tracks for tracks with  $p_T > 10$  GeV.

Tracks with  $p_T > 0.5$  GeV are less prone than lower- $p_T$  tracks to inefficiencies and systematic uncertainties resulting from interactions with the material inside the tracking volume.

After event selection, the analysis is based on approximately 17 million events containing approximately 300 million tracks. For the PYTHIA 6 generator and for the PYTHIA 8 generator, which has a harder diffractive model than the former, the contribution to the event shape observables from diffractive events is negligible when requiring six or more tracks in the event.

## VI. BACKGROUND CONTRIBUTIONS

### A. Backgrounds

Backgrounds comprise beam-induced events, due to beam-gas and beam-material interactions, as well as non-beam background, from cosmic-ray interactions and detector noise. The contribution of these background events remaining after the event selection is estimated using the number of pixel hits not associated with reconstructed tracks. This multiplicity includes unassigned hits from low- $p_T$  looping tracks, but is dominated at higher multiplicities by hits from charged particles produced in inelastic interactions of protons with the residual gas inside the beam pipe. The vertex requirement removes most of the beam background events and the residual contribution is below 0.1%. As the level of background is very low, no explicit background subtraction was performed.

### B. Secondary track fraction

The primary charged particle multiplicities are measured from selected tracks after correcting for the fractions of secondary and poorly-reconstructed tracks in the sample. The potential background from fake tracks is found from MC studies to be less than 0.01% [17].

Non-primary tracks arise predominantly from hadronic interactions, photon conversions to positron-electron pairs in the detector material and decays of long-lived particles. For  $p_T > 0.5$  GeV the contribution from photon conversions is small. The systematic uncertainty from secondary decays is included in the uncertainties associated with the tracking performance.

## VII. CORRECTION TO PARTICLE LEVEL

To facilitate comparison with theoretical predictions and other measurements, the event shape distributions are presented at particle level for charged particles, after correction for trigger and event selection efficiencies, as well as detector resolution effects. A two-step correction procedure is used: first, corrections for event efficiency are applied, followed by an additional bin-by-bin correction to account for tracking inefficiencies, possible bin migrations and any remaining detector effects.

### A. Event-level correction

Trigger and vertexing efficiencies are taken from a previous analysis using the same data sample [17]. The efficiency of the MBTS trigger is determined from data using a control trigger and found to be fully efficient for the analysis requirement of at least six tracks. The vertex reconstruction efficiency is also measured in data by taking the ratio of the number of triggered events with a reconstructed vertex to the total number of triggered events. This ratio is also found to be very close to unity. The total correction applied to account for events lost due to the trigger and vertex requirements is less than 1% and it varies very weakly with the number of tracks associated with the primary vertex.

### B. Bin-by-bin correction

The event shape observables presented here are sensitive to changes in the configuration of the selected tracks. Applying average track efficiencies to individual tracks on a track-by-track basis and reweighting tracks distorts the event shape distribution. A more robust approach is to apply bin-by-bin corrections to find the event shape distribution at particle level. Such a bin-by-bin correction is applied to all distributions after applying the event-level efficiency corrections described above.

The correction factors  $C_{\text{bin}}$  are evaluated separately in each bin for each event shape observable,

$$C_{\text{bin}} = \frac{V_{\text{bin}}^{\text{Gen}}}{V_{\text{bin}}^{\text{Reco, eff corr}}}, \quad (7)$$

where  $V_{\text{bin}}^{\text{Gen}}$  and  $V_{\text{bin}}^{\text{Reco, eff corr}}$  represent the generator level MC value of the bin content and the reconstructed MC



value after applying the event-level efficiency corrections for each bin, respectively. The corrected value of the bin content for an observable is found by multiplying the measured bin content by the corresponding correction factor. The bin sizes are chosen to be consistent with the resolution of the correction procedure.

The correction factors are calculated using the two different models implemented in PYTHIA 6 AMBT1 and Herwig++. This correction accounts for bin-by-bin migrations and tracking inefficiencies. For each distribution, the unfolding factor is typically within  $\pm 10\%$  of unity for most of the range and very close to unity for the average values. The difference from unity becomes more pronounced at the statistically limited edges of the distributions. The correction factors for the inclusive distributions of the three event shape observables are shown in the bottom panels of Fig. 1 for the two MC event generators mentioned above. Though the two MC generators have different distributions, the bin-by-bin correction factors are similar.

### VIII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties on the measured distributions are assessed with the following sources of uncertainty included:

**Tracking:** The largest of the systematic uncertainties for the tracking inefficiency [17] are found to be due to the material description in the inner detector. This is determined to affect the efficiency by a relative difference of 2% in the barrel region, rising to  $\sim 7\%$  for  $2.3 < |\eta| < 2.5$ , for tracks with  $p_T > 0.5$  GeV. The contribution of the propagated uncertainty to the distributions of the event shape variables is found to be less than 1%.

**Bin-by-bin correction model dependence:** The remaining contributions to the overall systematic uncertainty result from the specific correction method used in this analysis. The bin-by-bin corrections in general depend on the number of charged particles and their  $p_T$  distributions, so there is some dependence on the event generators. In order to estimate this uncertainty, it is necessary to compare different plausible event generators, which deviate significantly from each other, but still give predictions close to the data. The corrected results using the two very different PYTHIA 6 AMBT1 and Herwig++ models are compared. As these two generators use very different soft-QCD models the difference is assigned as a systematic uncertainty. The generated and reconstructed distributions are shown in Fig. 1 for the two MC event generators and compared with the detector-level data. Since this uncertainty is independent of any efficiency systematic uncertainties, it is added in quadrature with the efficiency systematic uncertainty and the statistical uncertainty.

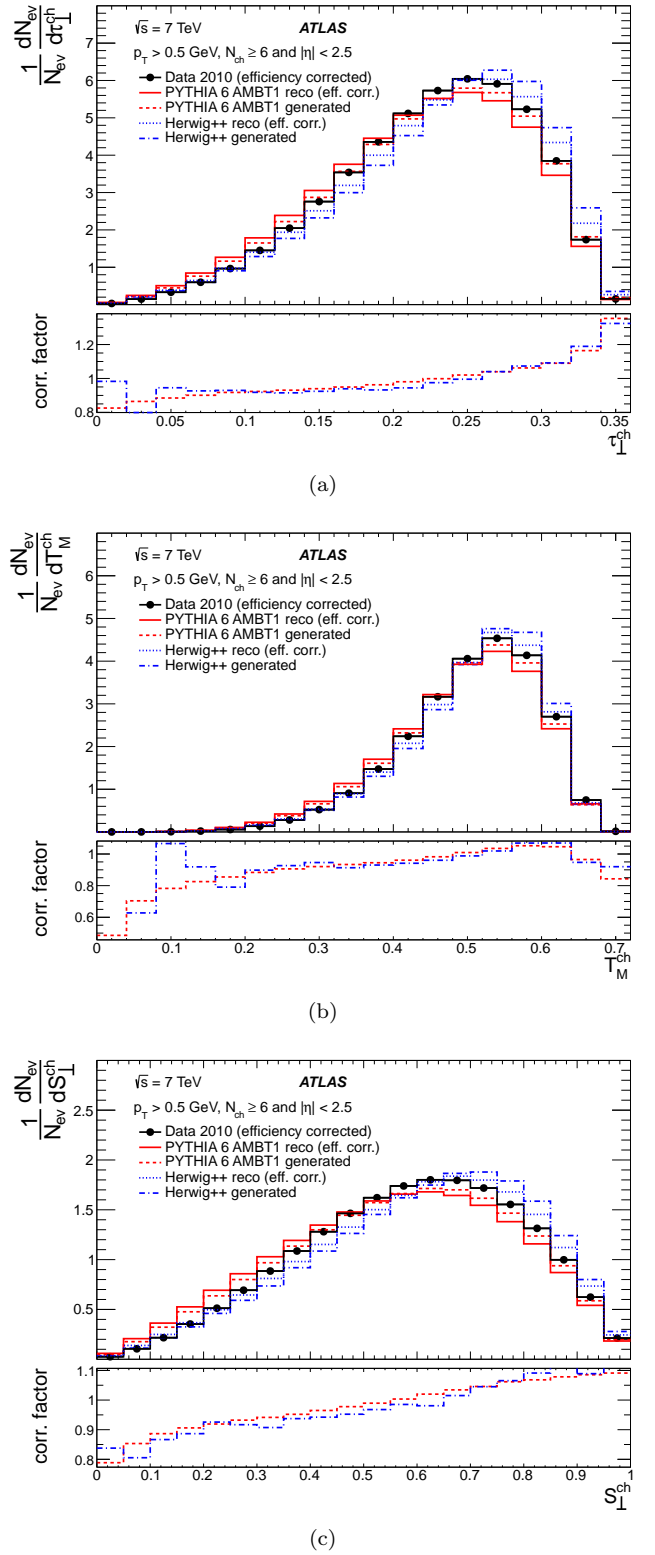


FIG. 1. The generated and reconstructed MC distributions for transverse thrust, thrust minor and sphericity are shown in the top half of each plot. The correction factors are shown at the bottom half for PYTHIA 6 AMBT1 and Herwig++ default tune. The data are shown with only the efficiency corrections and statistical uncertainties.

### Statistical uncertainty of bin-by-bin correction:

In addition to the model-dependent uncertainty in the bin-by-bin correction, there is also a statistical uncertainty due to the finite size of the MC sample. The statistical fluctuations of the PYTHIA 6 AMBT1 correction factor are found to be negligible for most of the distributions, increasing to a few percent in the tails of the distributions. This is also added to the overall systematic uncertainty estimate.

The systematic uncertainty due to the small number of residual multiple proton-proton interactions is estimated to be negligible.

Table I lists representative values for the various contributions to the systematic uncertainties for all the event shape observables away from the edges of the distributions.

TABLE I. Summary of systematic uncertainties in %.

Trigger and vertex efficiency	< 0.1
Track reconstruction	0.1 – 0.5
Correction model difference	1 – 5
PYTHIA correction stat. uncertainty	0.1 – 2
<b>Total systematic uncertainty</b>	<b>1 – 5</b>

## IX. RESULTS AND DISCUSSION

The distributions of the transverse thrust, thrust minor and transverse sphericity are presented in Figs. 2 and 3, for three different values of the minimum  $p_T^{\text{lead}}$ . As in previous measurements [18], the  $p_T$  of the leading charged particle is used to probe the emergence of a jet-like structure. The behavior of the average values of the shape variables as functions of the charged particle multiplicity,  $N_{\text{ch}}$ , and transverse momentum scalar sum,  $\sum p_T$ , is presented in Fig. 4. Predictions from PYTHIA 6 AMBT2B, PYTHIA 6 DW, PYTHIA 6 Z1, PYTHIA 8 A2 and Herwig++ UE7-2 models are also shown. AMBT2 is chosen instead of AMBT1 used to correct the data back to the particle level because it shows a slight improvement in reproducing the distributions of charged particle transverse momentum and multiplicity.

The inclusive distributions shown in Figs. 2 and 3 indicate a prevalence of high sphericity events. The shape of the transverse thrust and thrust minor distributions does not change appreciably upon increasing the lower limit of  $p_T^{\text{lead}}$  to 2.5 GeV, while a slight shift toward less spherical events and a broadening of the distributions is observed for events with  $p_T^{\text{lead}} > 5$  GeV. The mean of the transverse thrust and thrust minor respectively changes from 0.23 and 0.51 for inclusive distributions to 0.22 and 0.48 for distributions with  $p_T^{\text{lead}} > 5$  GeV. The transverse thrust

and thrust minor have little sensitivity to the leading charged particle transverse momentum threshold in the explored range. In contrast, the distribution of transverse sphericity shows a clear transition from spherical toward dijet-like events in the same  $p_T^{\text{lead}}$  range.

The mean values of event shape observables as functions of  $N_{\text{ch}}$  and  $\sum p_T$  are shown in Fig. 4. They are seen to increase to values largely consistent with the position of the maxima of the corresponding differential distributions with  $p_T^{\text{lead}} > 0.5$  GeV. Before reaching the plateau, for low values of  $N_{\text{ch}}$  and  $\sum p_T$ , the mean values of the event shape variables correspond to less spherical events. This can also be seen in the differential distributions as the lower limit on the leading charged particle transverse momentum is reduced. At very high values of  $N_{\text{ch}}$  and  $\sum p_T$ , the mean values indicate more spherical events.

In general, the MC models predict fewer high sphericity events than the data. However, the Z1 tune does a reasonable job of reproducing all of the distributions. The AMBT2B prediction shows better agreement for the inclusive distributions in Figs. 2(a), 2(b) and 3(a), than the PYTHIA 8 A2 tune and Herwig++ UE7-2 tune predictions. The PYTHIA 6 DW tune predictions are consistently furthest from the data, as observed for the charged particle multiplicity and  $p_T$  distributions [17] also. It is interesting to note that AMBT2B does not describe the event shapes very well, even though it has been constructed to model the data using inclusive distributions of charged particle multiplicity and transverse momentum presented in Ref. [17]. This suggests that event shape observables may be useful for tuning MC in the future.

For events with a higher  $p_T^{\text{lead}}$ , the Z1 tune provides the best description of the data, followed by Herwig++. In Figs. 2(c) and 2(d), with  $p_T^{\text{lead}} > 2.5$  GeV, for transverse thrust and thrust minor, the PYTHIA 8 A2 tune describes the data at a similar level as the PYTHIA 6 AMBT2B tune. With the exception of tune Z1, all of the models significantly overestimate the fraction of dijet events. For the transverse sphericity, shown in Fig. 3(b), the different PYTHIA tune predictions, other than Z1, are similar. All models tend to reproduce the data selected with  $p_T^{\text{lead}} > 5$  GeV better, as seen in Figs. 2(e), 2(f) and 3(c). The Z1 tune again provides the best description of the data, followed by Herwig++ and PYTHIA 8 A2. For this distribution, the DW tune also provides the same level of agreement as the other tunes.

The differences of the MC distributions with respect to the measured event shape distributions do not however yield more than a 5 – 10% shift in their corresponding mean values. With the exception of PYTHIA 6 DW, the MC models seem to predict the plateau value reasonably well in Fig. 4. The mean values of all event shape variables increase up to  $N_{\text{ch}}$  of about 30, or up to  $\sum p_T$  of about 30 GeV and tend to saturate at higher values of  $N_{\text{ch}}$  and  $\sum p_T$ .

The ALICE collaboration has measured the transverse sphericity distribution in inelastic 7 TeV  $pp$  collisions [13], selecting charged particles with  $|\eta| < 0.8$ . The behavior

of mean transverse sphericity as a function of multiplicity exhibits a similar behavior to that observed here, with the data lying at higher values than predicted by MC models.

## X. CONCLUSIONS

The event shape observables, transverse thrust, transverse thrust minor, and transverse sphericity, have been measured requiring at least six charged particles per event, in low pile-up minimum bias proton-proton collisions at  $\sqrt{s} = 7$  TeV. The distributions and mean values have been compared to a number of MC model predictions for various tunes of the minimum-bias and underlying event models. The dependence of the event shapes on the number of charged particles, on the sum of  $p_T$  and on the leading charged particle  $p_T$  has been studied.

The distribution of transverse sphericity shows a transition from spherical events toward a dijet structure as  $p_T^{\text{lead}}$  increases, while transverse thrust and thrust minor are much less sensitive. The dependence of the event shape mean values as functions of  $N_{\text{ch}}$  and  $\sum p_T$  is similar. For all variables, a slow variation is observed at low multiplicity and a saturation towards more spherical events at higher multiplicity. No evidence is observed for a dijet structure at the highest measured values of  $N_{\text{ch}}$  and  $\sum p_T$ . All MC generators underestimate the fraction of spherical events and none reproduces accurately the event shape distributions. The MC tunes based on the properties of the underlying event show in general better agreement with the data than those based on the inclusive distributions measured in minimum-bias events. The PYTHIA 6 with the Z1 tune provides the most accurate description for the distributions presented in this analysis, but the MC agreement could still be improved. These measurements provide information complementary to inclusive particle distributions and thus they are useful for improving the MC description of minimum-bias collisions at the LHC.



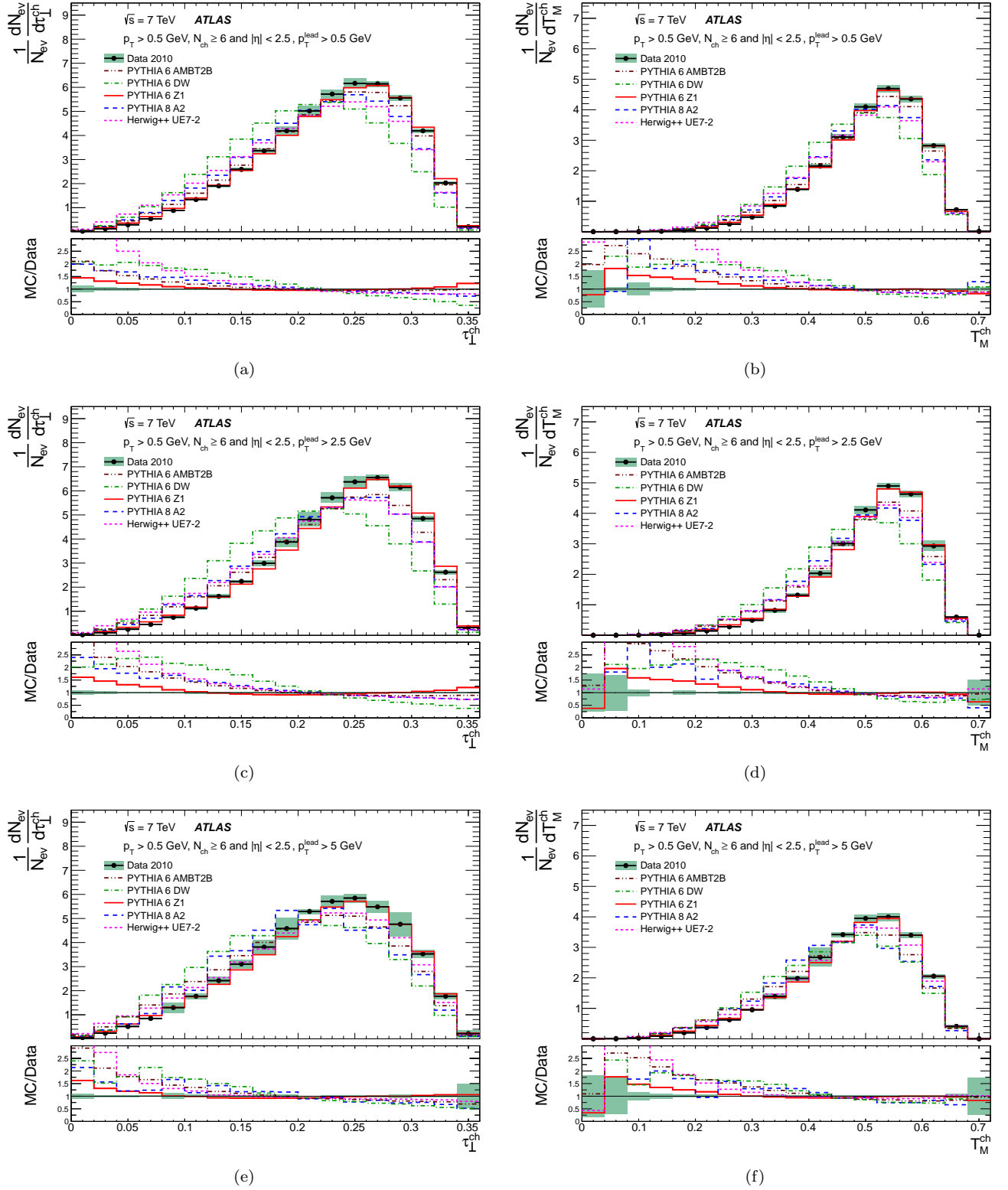
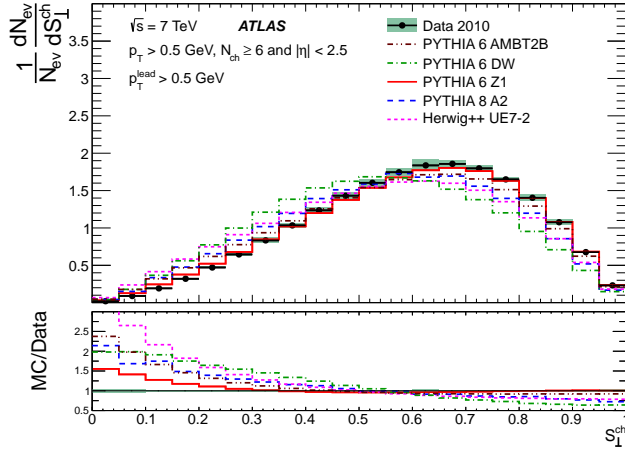
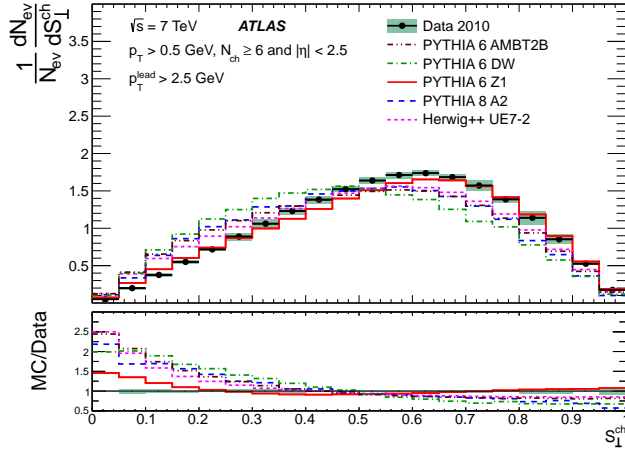


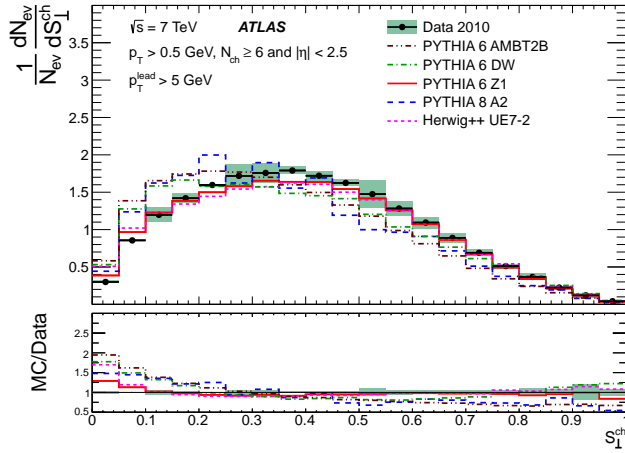
FIG. 2. Normalized distributions of transverse thrust (left) and transverse thrust minor (right) for particles with  $p_T > 0.5$  GeV and  $|\eta| < 2.5$  for different requirements on the transverse momentum of the leading charged particle,  $p_T^{\text{lead}}$  (top to bottom). The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty.



(a)



(b)



(c)

FIG. 3. Normalized distributions of transverse sphericity for particles with  $p_T > 0.5$  GeV and  $|\eta| < 2.5$  for different requirements on the transverse momentum on the leading particle,  $p_T^{\text{lead}}$  (top to bottom). The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty.

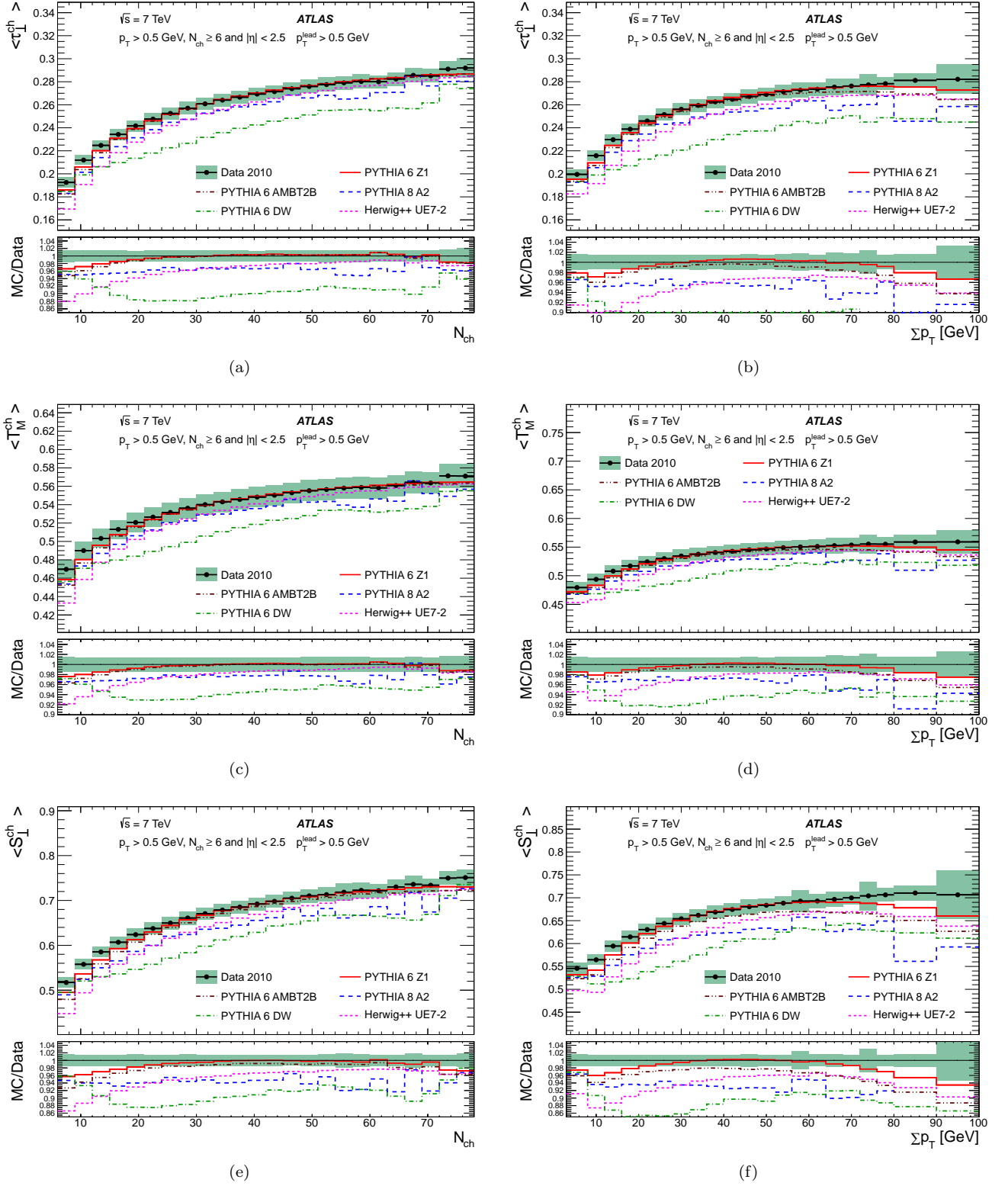


FIG. 4. Mean values of transverse thrust, transverse thrust minor and transverse sphericity (top to bottom) with  $p_T > 0.5$  GeV and  $|\eta| < 2.5$  versus charged particle multiplicity of the event (left column) and versus charged particle transverse momentum scalar sum of the event (right column) for transverse momentum of the leading particle  $p_T^{lead}$  of 0.5 GeV. The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty.

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